CAAD and Conceptual Design Collaboration between Architects and Structural Engineers

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Laurens Luyten[1]
[1]*Department of Architecture, KU Leuven, campus Sint-Lucas*

[1]*Laurens.Luyten@kuleuven.be*

Architectural design benefits from a design collaboration between architect and engineers that starts early in the design process. This paper presents a proposal for a new structural language developed to support an early design collaboration between architect and structural engineer. This language expresses the essential characteristics of the conceptual design of the structural engineer, and requires a limited amount of structural engineering knowledge for the architect to comprehend. The language is evaluated in different case studies with architecture and interior architecture students: they show the students' appreciation as it is found easy to learn and use, and a helpful tool in conceptual design collaboration with a structural engineer. Although the language is developed for manual 3D sketching, the paper briefly indicates its potentials for digital 3D representations and more intelligent CAAD like Multi-Agent System (MAS).

Keywords: *conceptual design collaboration, architect, structural engineer, structural language*

CAAD AND CONCEPTUAL DESIGN IN A TEAM WITH VARIOUS EXPERTS

Architectural design most commonly involves a collaboration of various design experts (e.g. architect, structural and acoustic engineer) with interdependent design outcomes: design decisions of one expert can importantly influence the quality of another expert's design outcome. Therefore a collaboration of architects and engineers starting already in the conceptual phase of the design process is a valuable asset to control the overall quality of the architectural design outcome.

This collaboration of architects and engineers is influenced by their differences in design cultures and knowledge, which start in their education (Salvadori 1991) and involve different modes of thinking (i.e. analytic versus synthetic) (Peters 1991; Akin 2001; Pfammatter 2000; Hurol 2014). Structural engineers for example are critical towards architects' lack of structural understanding and their seeking of structural advice too late for optimal structural solutions, while architects are disappointed by engineers' poor engagement with the architectural design ideas and are afraid engineers stifle their design explorations

(Charleson & Pirie 2009; Hurol 2014).

Emmitt and Gorse (2003) argue that architects and engineers need to possess mutual knowledge and experience in each other's discipline to be successful in their design communication. Zaccai and Bastick bring it a step further (Lerdahl 2001): to enable a successful collaboration for innovative or creative design, there is a need for overlap of expertise between architects and engineers. Parasonis and Jodko (2013) even advocate to complete this collaboration team with a different type of professional with training and/or experience in both professions.

Effort has been made to support the collaboration of architects and engineers through software which facilitates information sharing, task coordination and conflict resolutions (Wang et al. 2002). One of the emerging technologies is Multi-Agent System (MAS), which "consist of self-contained, knowledge-based systems that are able to tackle specialist problems and which can interact with one another (and/or with humans) within a collaborative framework" (Ren et al. 2011, p.537).

A more established technology in collaborative design is Building Information Modeling (BIM) which enables digital representations of physical and functional characteristics of an architectural design object. Here, research states that a single representation of an architectural design object is an insufficient tool for multi-disciplinary collaboration: because each discipline has its own understanding of a design object, its representation should be multiple according to the different discipline-specific understandings of architects and engineers (Fruchter et al. 1996; Rosenman & Gero 1996; Rosenman et al. 2005). Lee et al. (2014) argue for a distinction between a "private" representation of the data model adapted for a specific discipline, and a filtered "public" version which is shared between all design participants. Such filtering of information could then be intelligently handled by agents in MAS (Sariyildiz et al. 2002).

In spite of the importance of BIM in the industry of architecture, engineering and construction, Gu and London (2010) state that tools developed for the early design phases and for integration of conceptualisation are lacking within this BIM approach.

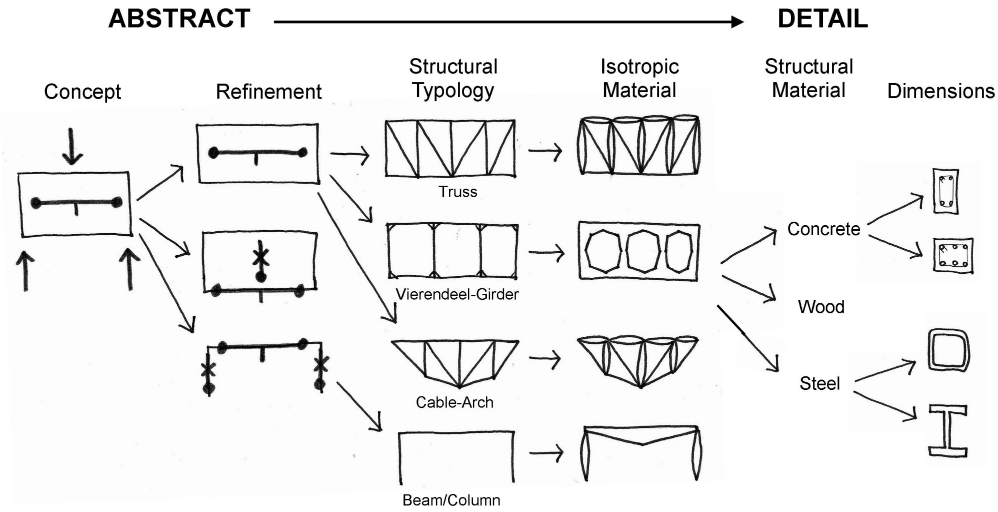
Certain architectural practices show that the use of CAAD leads to a fundamental change in design processes and design products (Hanna 2013). However, in design education this influence of CAAD-application has not been noticed. Furthermore, when it comes to conceptual design, students do not use CAAD that much (Salman et al. 2014). They prefer manual sketching to digital, and only later in the process, when the design project gets connected with its engineering aspects, CAAD becomes more implemented (Ibrahim & Pour Rahimian 2010): CAAD tools contain potentials to facilitate better communications in complex problem solving situations, but lack appropriate interface technology for conceptual design (Ibrahim & Pour Rahimian 2010; Attia & Andersen 2013; Schubert et al. 2013).

SYMBOLIC LANGUAGE TO COMMUNICATE THE CONCEPTUAL DESIGN OF THE STRUCTURAL ENGINEER

To communicate the conceptual design of the structural engineer with the architect, the author developed a structural language of symbols within his doctoral work. Although it was developed for manual sketching of three-dimensional (3D) design models during face-to-face meetings, it has potentials for implementation in CAAD-software.

The language is developed to communicate structural information filtered for the architect in the early phase of the design process. It conveys the essential characteristics of a structural concept requiring a limited amount of structural engineering knowledge for the architect to comprehend. Understanding the structural logics of the engineer's conceptual design is essential for the architect to engage in her/his design exploration: understanding the structural concept provides the architect insight in the implication of his/her possible design alteration to the structural design without the need for additional structural advice.

Figure 1
Application of developed language for concept creation and refinement (left).



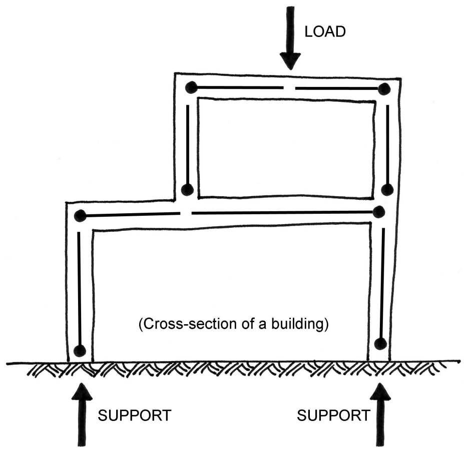
This language was developed by staging various early design collaborations between the author as structural engineer, and different architects or architecture students. During these collaborations it became apparent that the current engineering language of for example internal forces and general structural typologies, could be supplemented with a more abstract language to express structural concepts (Figure 1). Through trial and error in various design collaborations this new language was developed and evaluated (Participatory Action Research).

A language of four layers

The proposed structural language expresses structural logic as an important characteristic of a structural concept. It enables an abstract representation with a only a few symbols which find meaning in four different layers: (1) structural order, (2) structural function, (3) structural dimensions and (4) structural design possibilities.

(1) Structural order reveals the structural relations between different structural elements for a specific load case: it shows which element is supporting on which other element(s). It brings to the fore the path(s) a load follows throughout the different elements of the structural concept to its supports (Figure 2).

Figure 2
Example of structural order: identification of structural axis (-) and load paths (dot)



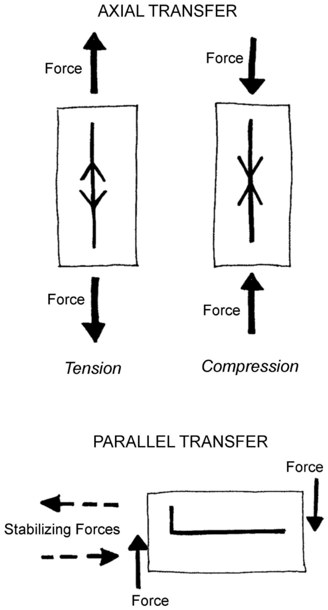


Figure 3
Structural dimensions layer: symbols for transfer of force.

To enable the structural concept to bring a load to its supports, each structural element is required to perform its own (2) structural function(s).The layer of structural function identifies the type of load transfer that needs to occur in a structural element: axial or parallel transfer of force (Figure 3), or axial or parallel transfer of moment (Figure 4).

The structural form of an element is determined by the required structural function(s) it has to perform. This is expressed in the layer of (3) structural dimensions. This leads to five major types of structural dimensions: one for each type of structural function except for axial transfer of force which is split into tension and compression (since in the latter buckling needs to be additionally considered for dimensioning). This means that expressing the characteristics of structural dimensions also reveals the underlying characteristics of structural functions that each element needs to perform (Figure 3 & 4).

The layer of (4) structural design possibilities links each conceptual element and its characteristics of structural dimensions (i.e. a structural conceptual element) with a wide range of possible (built) structural design solutions. These solutions as material form bring the conceptual design into the realm of built reality of structures - and also of architecture as each material form contains architectural qualities. As such a catalogue can be developed linking structural conceptual elements with a range of built examples (Figure 5).

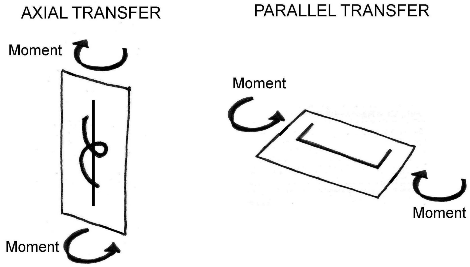


Figure 4
Structural dimensions layer: symbols for transfer of moment.

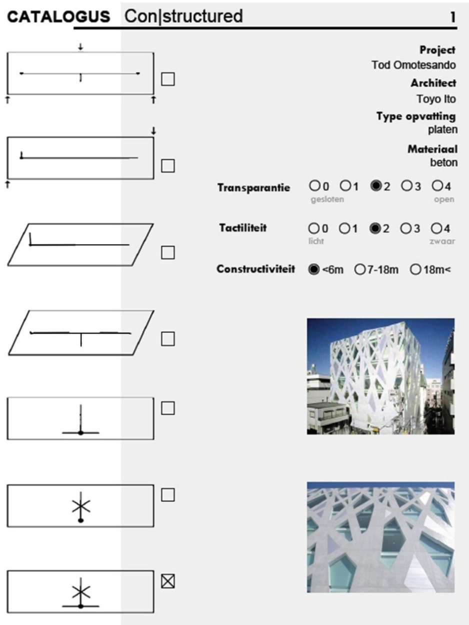


Figure 5
Example of catalogue entry for a structural conceptual element.

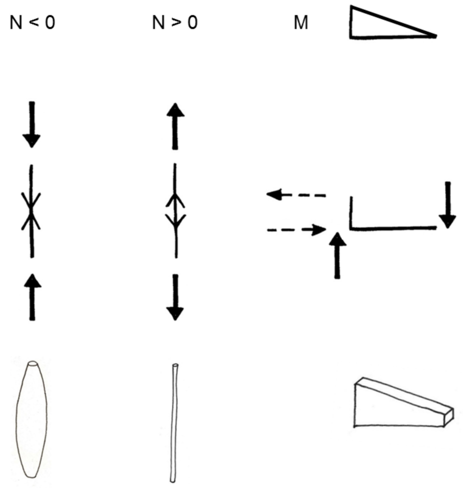


Figure 6
Symbols linking internal forces with material form.

The proposed language consists of six combinable symbols that express characteristics of the layers structural order and dimensions (Figure 3 & 4), and bridges the engineer's internal forces with the architect's material form (Figure 6).

Language application

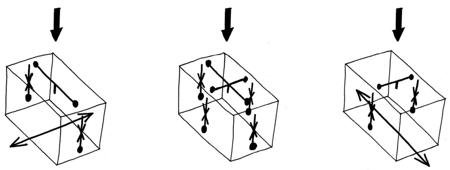


Figure 7
Articulation of conceptual design decisions: one form model with three possible structural concepts.

The structural engineer is able to express his/her structural concept by applying the proposed language of symbols to a 3D form model of the design project. This form model can be the result of the architect's conceptual design, on which each structural element then receives information about its structural order and dimensions. As such a communication develops of a rich 3D representation expressing on the one hand the structural behaviour of a system of conceptual elements, and on the other hand creating spatial experiences that relate directly to the architectural design. Such communication provides a common ground for design collaboration between architect and structural engineer when for example conceptual design decisions are evaluated. (Figure 7)

In summary, various qualities can be identified in the application of the proposed structural language:

- easily and quickly drawn.
- intuitively understandable.
- communicate structural logic in 3D representations (by expressing the characteristics of the layers structural order and structural dimensions).
- articulate conceptual design decisions of the engineer for negotiation (i.e. mainly the identification of the chosen structural elements, loads, supports, load paths, required function(s) of each structural element and the type of element connection).
- provide for more abstract building blocks of design creation (i.e. more conceptual than common structural typologies, which allows for the architect a wider design exploration).
- filter structural information for the architect (i.e. reduce the amount of engineering-specific knowledge required to understand structural logic, and focus information on decisive characteristics of structural dimensions).

EVALUATION OF DEVELOPED LANGUAGE

The proposed language is evaluated through its application in two case studies with architecture and interior architecture students in the educational practice of the author. In the first case study it is mainly evaluated as a communication tool, in the second as a collaboration tool in design.

Evaluation of language in an individual application of architecture students

The first case study consists of a seminar with seventy-eight architecture and interior architecture students in the last two years of their educational programme. These students are familiar with the traditional engineering languages (e.g. of internal forces) but uninformed about the new developed language. They are asked to express their own structural understanding of a built project of their own choice, through a presentation in their own chosen language(s). After handing in this presentation and a short introduction in the new structural language of the author, they are asked to express the same structural understanding of the built project with this new language in a new presentation (Figure 8).

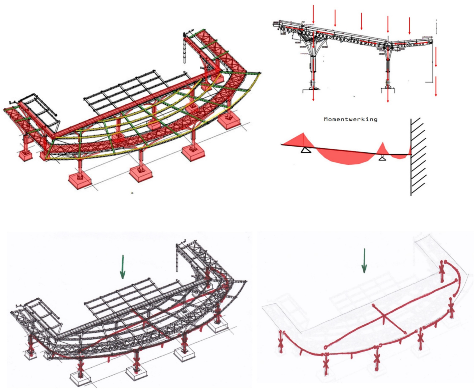


Figure 8
Student's example of similar structural story with traditional (top) and new (bottom) languages.

Through questionnaires most students (> 80%) express to find (1) the new structural language easy to learn and use as they appreciate its symbols as clear and intuitively understandable. (2) 90% of the students found that the essence of structural behaviour as they comprehend it, could be explained well with the new language.

When the author compares both presentations of the same structural story it shows that (3) when the structural behaviour is well understood by the students, both structural narrations are often almost equal, and that in most cases, the students are capable of using the language correctly.

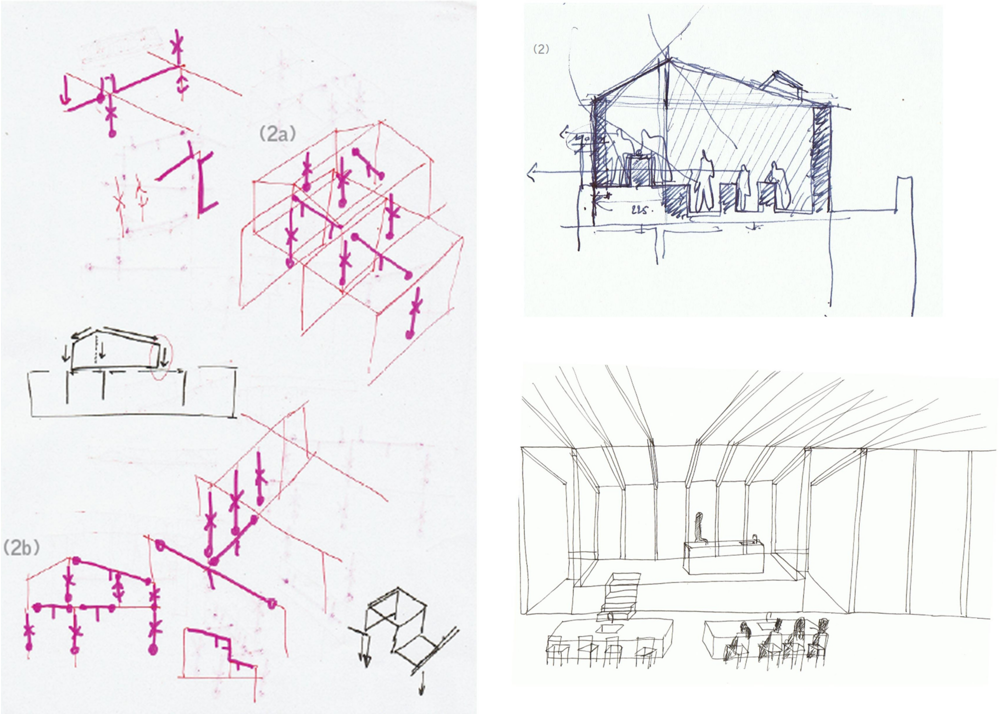
In the second part of this seminar, students are asked to develop structurally sound concepts by altering their investigated structural concept. In this exercise there is no obligation to apply the new language. Questionnaires show that (4) about half of the students feel that their general structural knowledge is increased by the use of this language. (5) 85% of the students find it an asset to be able to use this language for this variation design exercise: they appreciate not having to go into designing details and being able to work only with a more abstract conceptual structure. (6) 40% of the students that used the language during their design process express to have found new structural design ideas at some point through the use of this new language.

Even though there is a psychological effect for over-appreciation when trying something new (cf. Hawthorne-effect), this case study shows that in general (interior) architecture students evaluate this new language positively in regard to learning it, its ability to increase their structural understanding, and its qualities to communicate structural behaviour and to enable structural design.

Evaluation of language in design collaborations of architecture students and engineer

The second case study consists of six design collaborations between on the one hand the author as structural engineer, and on the other hand six architecture students and one interior architecture student, all in their master years, as architect. These collaborations occur in face-to-face meetings within a design studio setting spread over several weeks, and involve the participation of an additional tutor taking care of the architectural qualities of the various design projects. The collaborations start early in the design process and the communication on paper between architect and structural engineer occurs through the use of the new structural language. After the end of the design project, students fill in a questionnaire with open-ended questions and there is an follow-up discussion. This leads to the following findings:

Figure 9
Example of student's design project: conceptual structural design sketch and architectural proposition before (top) and after (bottom) structural consultation (left).



- Students describe the new structural language used in the face-to-face meetings as clear, direct, pure, intuitive, understandable and quick: you can learn it by using it; it does not need much explanation.

- Students state that the language is useful for the first phases of the design process, when there is a need for more abstract structural ideas, but that something 'more' is needed later on in the design process, when there is a need for more detailed information that this language does not provide.

- There is a limit on the amount of understandable information that can be communicated in one drawing. Thus in case of complex structures or too many load cases, more than one 3D view is needed.

- The language provides structural information on the level of an architect's design culture. Students value the visual communication (with the language) more than a spoken one.

- Some students say they find it essential to limit the number of different symbols in the language in order to gain more insight into the structural essence.

In addition, based upon his notes and the produced project results of the students, the author concludes that (1) the language enables him to quickly and easily write down the structural story of a conceptual design proposal, with the advantage to be (2) still consultable by students after the meeting is over. (3) The students seem able to grasp the expressed structural behaviour of the structural proposition and if necessary change the presented structural form model within sound structural logic.

CAAD POTENTIALS OF THE NEW STRUCTURAL LANGUAGE

The presented language is developed for manual sketching of 3D design representations in face-to-face meetings in which speed of communication is essential. Its application requires important 3D drawing abilities of the designer to produce these representations, and has limitations to express complex problems. Therefore the new language has potentials for application in CAAD since the symbols can simply be adapted to digital 3D representations in which more complex problems can be expressed: digital layers can be turn off or on, dynamic views of the model allow for more complex 3D communication and symbols can simply be added to an existing digital architecture model.

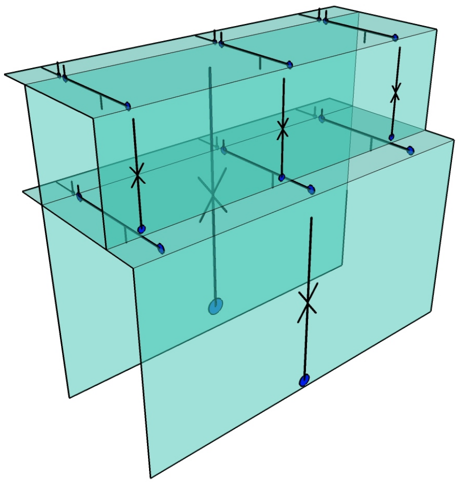


Figure 10
Example of application of the structural language in a digital 3D model

Still, for a successful implementation during conceptual design collaboration, an appropriate interface technology is required which allows for a swift communication between architect and structural engineer, and also for visual and tactile feedback which contributes to an internal design dialogue also called "visual thinking" (cf. Schubert et al. 2013).

Further potentials for this language in CAAD lie in MAS, in which agents are used to:

- filter "private" structural engineering models into "public" models by translating the engineer's information overload on internal forces into a more abstracted structural essence through the use of the new language.
- link structural conceptual elements with an array of built design possibilities through data mining for design exploration (cf. Sariyildiz et al. 2002).
- check the structural load path, and vertical and horizontal stability of the conceptual design as defined by the allocated symbols of the new language on the 3D form model.

CONCLUSIONS

The overall quality of an architectural design project profits from a design collaboration between architect and engineers that starts early in the process. However differences in design cultures and knowledge ask for special attention when architect and engineer work together during conceptual design: for example, an overlap of expertise is preferred to enable a rich communication and the development of innovative design.

The design collaboration between architect and engineer finds support in different possibilities within Computer Aided Architectural Design (CAAD) like Building Information Modeling (BIM) or the emerging Multi-Agent System (MAS). However when it comes to collaboration in the early phases of design, progress is still required.

The presented structural language is developed for early design collaboration between architect and structural engineer. It provides 3D representations that express and enable to understand the structural essence of a conceptual design of the structural engineer, with a minimum requirement of engineering specific knowledge. The language consists of symbols to express structural order, function and dimensions of the structural conceptual elements, and contains a built-in relation between these abstract elements and a catalogue of possible design solutions.

Case studies show that for most architecture and interior architecture students the new language is easy to learn and use, and that the language even helps an important number of students to conceptually design structures. When designing in collaboration with a structural engineer, the language is well received with (interior) architecture students as a communication and design tool in the early phases of design. However, during the later phases this language falls short as more detailed and accurate information exchange is required, which traditional structural languages can provide.

The language was developed for manual 3D sketching but has much potential for use in CAAD-software: first of all in simple 3D digital representation software, but also in more intelligent MAS. Here, further research is required.

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